Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **07 NOV 2014**	2. REPORT TYPE	3. DATES COVERED **01-10-2011 to 30-09-2014**

4. TITLE AND SUBTITLE **Protoype solid state quantum interface for trapped ions**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Regents of The Univerity of California,,The University of California, Berkeley,2150 Shattuck Ave, RM 313,Berkeley,,CA,94704**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Final report for “Protoype solid state quantum interface for trapped ions”.

Hartmut Häffner, UC Berkeley, Nov 7th 2014

Project period: October 2011 till September 2014

Abstract:

We study how to couple the motion of trapped ions to each other. For this we set up an ion trap apparatus with an electrically floating electrode connecting two trapping sites. We find that we can trap ions nearby such an electrically floating electrode. At the same time, we develop a method to cool and control motional modes not accessible with laser radiation, thereby relaxing requirements for optical access. We also measure the degree of polarization of anomalous heating and find it consistent with sources from the metal surface. We design a second generation trap with an integrated coupling electrode amenable to Ar-ion treatment. Finally, we develop a vision for QIP with electrons with the distinct advantages of avoiding laser technology and being inherently faster than trapped ions.

Narrative:

Goal of the experiments was to couple the motion two ions to each other via image currents induced in a normal conductor. For this we set up a surface trap with a movable wire. The wire was fabricated by evaporating gold on a fiber. By shadowing the fiber at two locations, three distinct conducting films were created. The film in the center was electrically floating with resistances greater than 1 giga-ohm to the other films and thus suitable as a coupling electrode. The main challenge was to bring this coupling electrode close to the ion trapped under UHV conditions and at the same time control the electrode’s mechanical vibrations and its electrical potential.

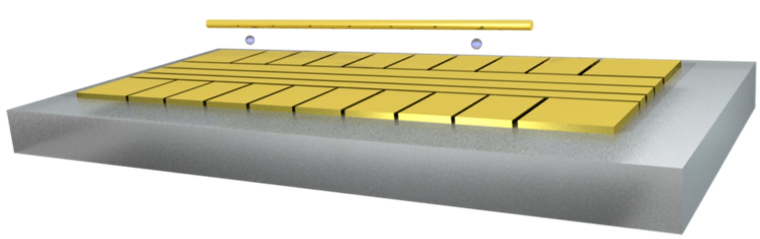

Fig. 1: schematics of the segmented surface trap with two ions (blue balls). Shown above the trap is only the central Gold film covering the fiber parallel to the trap axis.

We characterized the trap and found that we can tune the radial secular frequencies between 2 and 5 MHz and the axial frequency between 200 kHz and 1.2 MHz. The trapping positions and frequencies match with our electrostatic simulations on the level of a few percent. We developed a novel method to perform micromotion compensation based on monitoring parametric excitation fields generated by the RF-electrodes. This method is of particular importance for our wire experiments as it allows to compensate for electric stray fields perpendicular to plane of the surface trap. Compensation of such electric fields is typically not feasible with conventional micromotion compensation methods.

The coupling experiments require to trap two ions or small ion strings at two distinct trapping locations. We demonstrated such an arrangement by simultaneously trapping two ions spaced by 750 micrometers. Furthermore, we transported a single ion between those two zones.

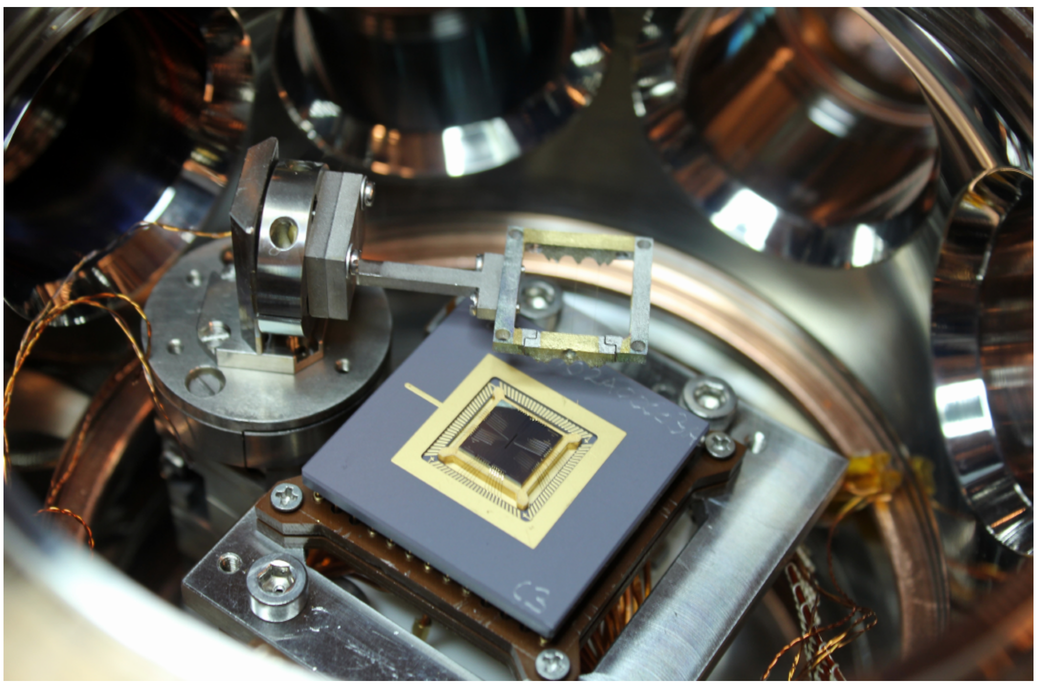

Fig. 2: The trap assembly. In the center is the ion trap mounted on a CPGA. Three fibers (barely visible), each coated with three electrically disconnected films of gold acting as wires, are spanned in the rectangle mounted on an arm. Piezo motors swing the arm over the trap and position the wire with micrometer precision above the trap.

We then proceeded to characterize the trap while bringing in the the wire. We were able to move the wire as close as 80 micrometers while maintaining stable trapping. Surprisingly, we did not have to change the trapping potentials substantially. This shows that the electrically floating electrode was nearly at ground potential (see Fig. 3).

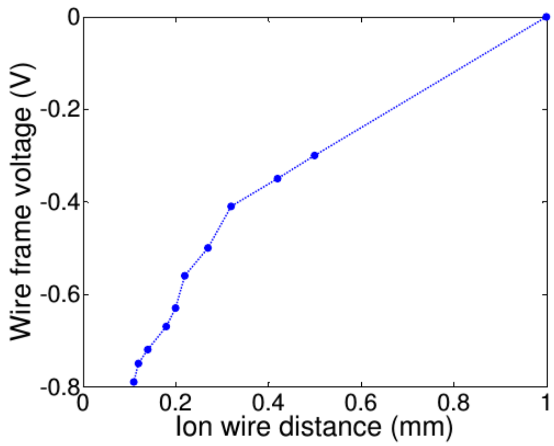

Fig. 3: Voltage applied to the wire frame (see Fig. 2) to compensate micromotion in the vertical direction. Here the smallest distance data recorded for was 110 micrometers. Less than 1 V on the wire-frame was required to compensate for micromotion and to maintain stable trapping. This shows, that the floating electrode was near ground potential.

The next step was to measure the electric field noise emerging from the wire. We found inconsistent results. In particular, the electric field noise in the direction where noise from the wire has no projection (along the wire) increased substantially while bringing in the wire. However, in the field direction where we expect the ions to heat up due the wire, we observed no influence of the ion-wire distance on the ion heating (see Fig. 4).

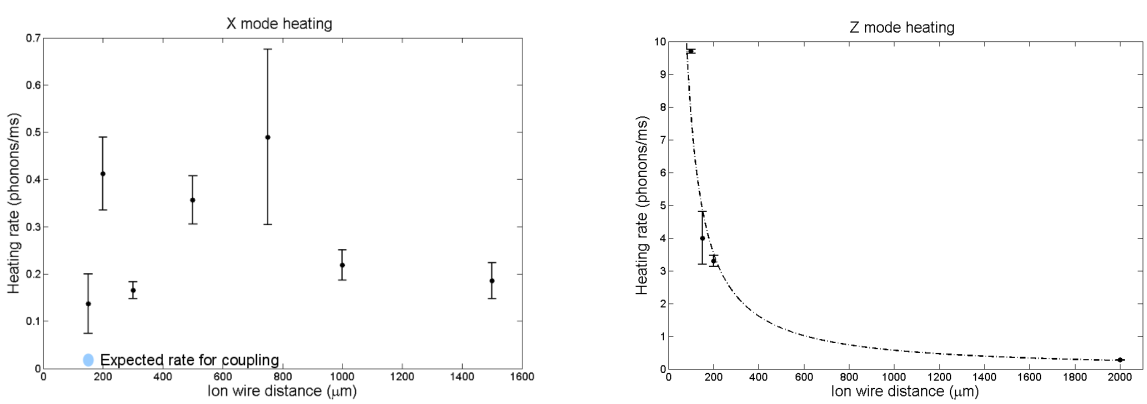

Fig. 4: Heating rate for the X-mode (left graph, motion orthogonal to the wire) and Z-mode (right graph, motion parallel to the wire). It is unclear why the Z-mode parallel to the wire is affected by the wire in the first place, in particular, since the X-mode is rather unaffected by the proximity of the wire.

While studying the details of this unexpected behavior, the wire fell from its support. After optical inspection, we concluded that the fiber did not detach where it was glued to the support, however, that the fiber itself mechanically broke apart. At this point we have no reasonable explanation how that could happen in UHV, especially since we did not exert external forces on it. We speculate that during fabrication the fiber was exposed to some chemical which slowly affected the mechanical integrity of the fiber glass. Furthermore, it must have broken at two distinct spots before it could have fallen down. Thus, it is likely that during our experiments, the fiber was only supported on one end, thus allowing for substantial mechanical vibrations. This in turn could explain our unexpected findings of the noise behaviour discussed above and shown in Fig. 4.

One crucial aspect we learned during those experiments is that the motional mode coupling strongest to the wire will be very hard to access with laser light. Therefore, we developed a scheme to parametrically couple two normal modes to each other by modulating the voltage of trap electrodes thus transferring population between two modes (see Fig. 5). Our scheme can be used to not only to measure heating rates of arbitrary modes, but also to perform two-mode squeezing and simultaneous cooling of many modes at the same time among other applications. We demonstrated the latter and cooled two motional modes simultaneously close to their ground-state. This work has been published in PRA (Gorman 2014). Most importantly for us, this method will allow us more freedom in designing the 2nd generation wire-coupling experiments as we can relax laser access requirements.

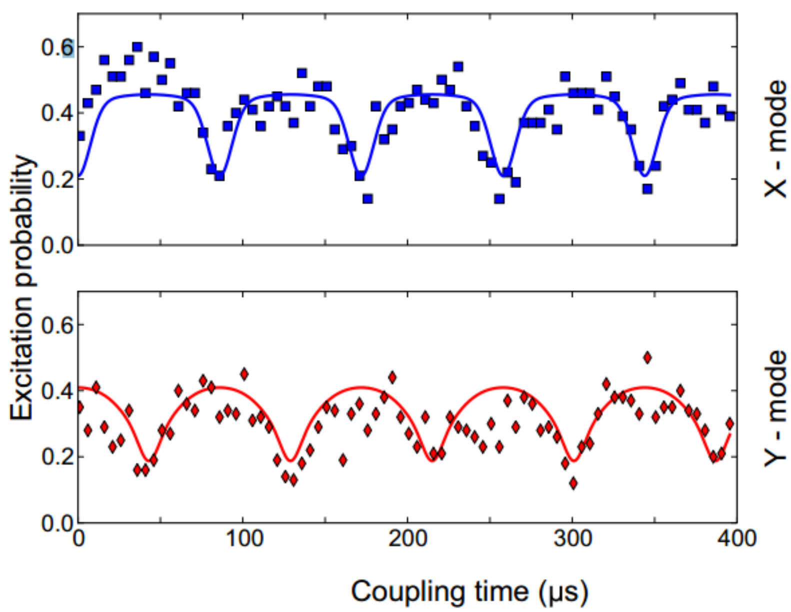

Fig. 5: Periodic energy exchange between the two radial modes while parametrically coupled. First the X-mode is cooled close to its motional groundstate (~0.2 motional quanta) while the Y-mode is left at the Doppler temperature on the order of 5 motional quanta. 40 microseconds after switching on the parametric coupling, the reduced excitation of the red sideband of the Y-mode reveals that now the Y-mode is near the ground state while the X-mode is hot.

We also applied the mode-coupling technique to surface science related issues and characterized anomalous heating. In particular, we measured the polarization of the electric field noise, i.e. its predominant direction. We found that heating normal to the conducting plane of the trap is about a factor of 4 higher than than parallel to the surface. Within measurement uncertainty, this is consistent with patch potential and surface adsorbate models predicting a factor of two. However, our measurements seem to rule out technical noise from noisy electronics. Distinguishing technical from surface noise is notoriously difficult, thus our measurements not only show an important fundamental property of surface noise but will also be helpful in eliminating technical noise and thus helping to perform more reliable studies of anomalous heating. We are finalizing the manuscript to publish this results.

In view of the mysterious failure of the mechanical stability of the fiber UHV, we feel that it is now time for an integrated coupling electrode. The fact that the piezo-electric stages used to move the wire are not very reliable and that we know now that we can trap near a floating electrode motivates us further (lack of this knowledge was why we used a movable wire in the first place). We also realized that we would benefit from the to-be coupled modes to be governed by DC rather than RF potentials as this will allow for low trap frequencies while maintaining substantial trap depth and high trap frequency stability.

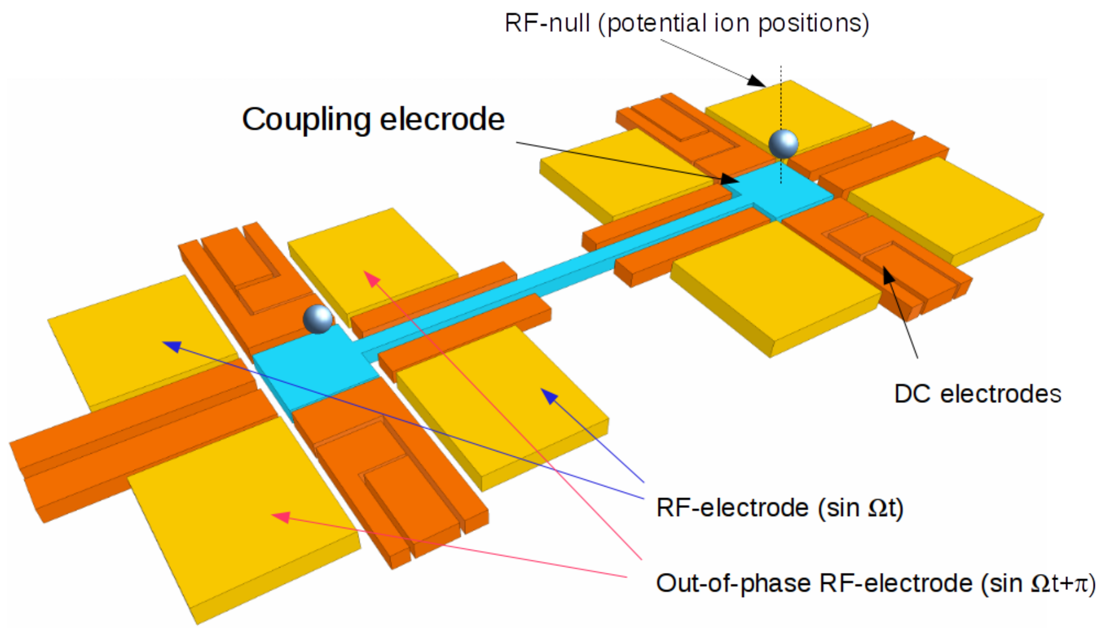

Fig. 6: Schematics of the new trap lay-out. Ions can be trapped at distances between 30 and 150 micrometers from the surface in the center of the RF electrodes (in yellow). The ion height can be tuned by applying DC voltages to the orange electrodes. Coupling is mediated by the blue electrode. We performed extensive studies on trap potentials, finding horizontal secular trap frequencies of 5 to 10 MHz and vertical ones ranging from 100 kHz to 5 MHz. The typical trap depth is on the order of 100 - 200 meV.

In this view, we came up with a rather novel trap design where the RF-null (the line of feasible trapping sites) is perpendicular to the surface (see Fig. 6). This is made possible by having two pairs (instead of one pair) of RF electrodes with opposite RF-phase such that the fields cancel along the symmetry axis. The trap should allow us to trap ions at a *in-situ* variable height between 30 micrometers and 150 micrometers and allowing for coupling energies of almost 100 Hz at 50 micrometers ion-electrode distance which would correspond to an entanglement time of 1.25 ms. The advantages of this trap design over our previous one are manifold:

- The trap frequency normal to wire (the blue electrode in Fig. 6) is purely given by DC fields. DC fields are inherently much more stable allowing for higher trap frequency stability, exhibit probably less noise, and allow for higher trap depth as compared to RF confinement.

- The planar design allows for Ar-ion treatment and thus to reduce heating rates by a couple of orders of magnitude. This treatment will be likely necessary to achieve entanglement.

- We can vary the ion height by changing only DC-voltages, thus allowing us to tune the ion-wire coupling as well as to study the distance scaling of anomalous heating (which is still under debate).

- Monolithic design, much less prone to misalignments and structural failures, such as experience with the wire.

While designing the new the trap, we tested the old trap for its properties to hold long ion chains. We trapped on the order of sixty ions. We now established optics to focus two qubit-lasers allowing us to probe the energy of individual ions in such a chain. Goal of the on-going experiments is to study the dynamics of quantum correlations between the spin degree-of-freedom and the motion of the ion crystal.

On the theory side, we proposed to couple electrons to each other with the methods discussed here. The advantage over ion experiments is a 100-fold speedup due to the much reduced mass of electrons. In the addition, the much higher motional frequencies of the electrons reduce the effect of the 1/f noise from anomalous heating and thus allow for bringing the electrons much closer to the trap surface. In this publication, we also study a novel parametric scheme which would allow us to couple the electrons oscillating at around 500 MHz to superconducting electronics with resonances about one order of magnitude larger. We published this work in NJP (Daniilidis 2013). Our paper thus develops the vision of an electron-based quantum information processing device. Tasks carried-out in conventional ion-trap quantum experiments by lasers would be taken over by microwaves, SQUIDs and LC-resonators: the electron motion would be cooled to its motional ground state with a time constant of 1 microsecond by coupling it to a high-frequency LC-resonator at 50 GHz. Quantum gates between the electrons can be implemented by the magnetic-field gradient method proposed by the NIST group in 2008 and demonstrated by the same group in 2011.

The low mass of the electrons allows for sub-microsecond gate times. Finally, read-out can be carried out by coupling the electron motion to a SQUID at the same time scale of less than 1 microsecond, again with a about 100-fold improvement in speed as compared to fluorescence based read-out for ions. Thus, this approach combines the speed and ease-of-use from solid-state QIP devices with superior coherence from atomic qubits.

Conclusions

We find that we can trap ions nearby an electrically floating electrode. We also perform micromotion compensation with restricted optical access. At the same time, we develop a method to cool and control modes not accessible with laser radiation, thereby further relaxing requirements for optical access. We also measure the degree of polarization of anomalous heating and find it consistent with sources from the metal surface. We design a second generation trap with an integrated coupling electrode amenable to Ar-ion treatment. Finally, we develop a vision for QIP with electrons with the distinct advantages of avoiding laser technology and being inherently faster than trapped ions.

Papers published during the review period:

N. Daniilidis, D. J. Gorman, L. Tian, and H. Häffner, Quantum information processing with trapped electrons and superconducting electronics, **New J. Phys. 15, 073017 (2013)**.

D. J. Gorman, P. Schindler, S. Selvarajan, N. Daniilidis, and H. Häffner, Two-mode coupling in a single-ion oscillator via parametric resonance, **Phys. Rev. A 89, 062332 (2014)**.